1. NAME OF INITIATIVE:

List of major collaborating institutions (including non-US partners).

NOνA (**N**uMI **O**ff-Axis ν_e **A**ppearance Experiment) (P-929)

The NOνA Proposal has about 160 authors from 34 institutions:

Argonne, **Athens**, **Caltech**, **UCLA**, Cambridge, **Fermilab**, College de France, **Harvard**, **Indiana**, ITEP, Lebedev, Louisiana State, **Michigan State**, Minnesota/Duluth, **Minnesota/Minneapolis**, Munich, Stony Brook, Northern Illinois, **Ohio**, **Oxford**, Rio de Janeiro, **Rochester**, **Rutherford**, **South Carolina**, **Stanford**, Texas A&M, **Texas/Austin**, **Tufts**, **Virginia**, **Virginia Tech**, Washington, William & Mary, Wisconsin, York

(major institutions {defined as ones with >3 people} are shown in **bold** above, and non-US institutions are shown in blue)

2. SCIENTIFIC JUSTIFICATION:

Physics goals. How does it fit into the global physics goals for the entire field.

The past two decades have seen great advances in our understanding of neutrinos. Underground experiments detecting neutrinos produced in the sun and in the earth's atmosphere have shown that neutrinos have mass and that they oscillate from one species to another as they travel. These oscillations arise because the neutrino species produced in particle decays (electron, muon, and τ-type neutrinos) do not have specific masses but are combinations of neutrino species (simply called 1, 2, and 3-type neutrinos) that do have specific masses. The average distance a neutrino travels before it oscillates is proportional to its energy and inversely proportional to the difference of the squares of masses of the underlying species of neutrinos. The probability that an oscillation will occur is related to a parameter known as a mixing angle.

The neutrinos that come from the sun are electron-type neutrinos that oscillate to muon and τ-type neutrinos, characterized by the mixing angle θ_{12} and an oscillation length (normalized to an energy of 2 GeV) of approximately 35,000 km. Neutrinos produced by cosmic rays in the earth's atmosphere are primarily muon-type neutrinos that oscillate to τ–type neutrinos, characterized by the mixing angle θ_{23}, and an oscillation length (again normalized to an energy of 2 GeV) of approximately 1,000 km. A third type of neutrino oscillation is possible: the oscillation of muon-type neutrinos to electron-type neutrinos at the atmospheric oscillation length. These neutrino oscillations, which so far have not been observed, would be characterized by the mixing angle θ_{13}. The study of this last category of neutrino oscillations is the main goal of NOνA.

The significance of the search for these oscillations is that if they exist, i.e., if θ_{13} is not zero, then we will ultimately be able to determine the ordering of the neutrino masses and measure CP violation in neutrino oscillations. There is widespread belief that the very small neutrino masses are related to physics at an extremely high-energy scale, one that cannot be studied directly with accelerator beams. There is also theoretical speculation that CP violation by neutrinos could be one aspect of understanding why the universe is composed solely of matter, rather than equal amounts of matter and antimatter. In addition to the main goal of measuring θ_{13}, NOνA would also improve measurements of $\sin^2 2\theta_{23}$ and Δm^2_{23} and contribute to searches for sterile neutrinos.

NOνA would utilize U.S. investment in the NuMI beamline by building a second-generation detector (following the first-generation detector MINOS), which would have the primary physics goal of measuring θ_{13} with approximately a factor of 10 more sensitivity than MINOS.

NOνA would be sited along the NuMI beamline at 810 km and to the side of the NuMI beamline by 12 km, near the US-Canada border in northern Minnesota. This is farther from Fermilab than the MINOS experiment at 730 km. The 12 km off-axis site results in a nearly monochromatic neutrino beam of energy ~ 2 GeV to be contrasted with the broader energy beam available on-axis for MINOS. The long 810 km NOνA baseline would be unique in the world neutrino program and would naturally have a larger matter effect (ν_e interactions in the earth's crust) from the long path length. This long baseline gives NOνA a superior ability over any contemplated experiment to resolve the mass hierarchy in the neutrino sector.

Globally, experiments are being contemplated in Europe (beta beam over a 130 km baseline) and Japan (off-axis beam from JPARC to the 50kT SuperKamiokande detector over a 295 km baseline, called T2K). Reactor experiments in the U.S. or elsewhere in the world can also contribute to the θ_{13} search. Of these possibilities, T2K is further advanced and should begin taking data in 2010. Meanwhile the Fermilab NuMI beam begins producing neutrinos in 2005, providing an excellent window of opportunity for NOνA and the U.S. program to lead the way in this field.

Since there are three unknown parameters to be measured — θ_{13}, the ordering of the mass states, and the parameter that measures CP violation — a third measurement may eventually be required in addition to neutrino and antineutrino measurements in NOνA to determine all three parameters. The third measurement could be done by building a second NOνA detector near the NuMI beamline, or by combining NOνA measurements with those taken elsewhere on different length baselines

We view NOνA as a second step (following MINOS) in a step-by-step Fermilab program to measure the unknown parameters of neutrino oscillations. Each step will provide guidance on the optimum direction for the succeeding step.

3. VALIDATIONS FOR SCIENTIFIC JUSTIFICATION:

Examples of recommendations and supporting statements from the committees, panels, and the community at large.

The NOνA collaboration submitted a proposal to Fermilab for consideration by the Fermilab Physics Advisory Committee at the April, 2004 meeting. Additional written and presented materials were submitted for the June 2004 meeting to address questions raised by the PAC, to further quantify and refine the physics case, and to describe the ongoing R&D program.

The PAC said that to establish a compelling physics case, NOνA must meet the following criteria:

1) Uniqueness. Does NOνA have a unique physics capability not achieved by any other experiments worldwide?

2) Competitiveness with T2K, the Japanese program discussed above. Can NOνA compete with T2K program within a similar time frame?
3) Competitiveness and/or complementarity with future reactor experiments. Can NOνA compete with their sensitivity or provide information not obtainable from the reactor experiments?
4) Capability for evolution with the future neutrino program. Would NOνA allow natural progression to CP violation studies with a future proton driver with the currently proposed detector at the same location?

In the near future, NOνA would be the only experiment in the world that could potentially determine the mass hierarchy for a range of the relevant parameters. Its performance would be competitive with T2K in other areas, namely the search for electron appearance for $\sin^2 2\theta_{13} \geq 0.01$ and precision measurements of $\sin^2 2\theta_{23}$ and Δm^2_{23}. NOνA's electron appearance signature, which would be statistically limited, is complementary to the disappearance signature from the reactor experiments, which would be systematically limited and insensitive to matter effects and CP violation. Observing electron appearance would make the case for a proton driver even more compelling, and would possibly motivate a second detector. **The Committee found that the proposal can meet the above four criteria, if the experiment can be built in a timely manner.**

Following the construction of a proton driver, NOνA, equipped with a second off-axis detector, would reach its full capability. It would be able to determine the mass hierarchy for any value of δ down to $\sin^2 2\theta_{13} \geq 0.02$, which in turn will allow 3 sigma discovery of CP violation for a large range of δ. A combination with the data from T2K-II would extend the reach in CP violation to much smaller $\sin^2 2\theta_{13}$.

In the context of a coherent long-range neutrino program, the PAC found the case for NOνA compelling. The physics goals are to first measure θ_{13}, then to resolve the mass hierarchy and to discover CP violation in neutrino oscillations. This is an attractive approach, proceeding in incremental steps that allow for decisions based on outcomes at each stage of the program, taking into account new results from other experiments, as well as funding constraints.

The PAC strongly endorsed the physics case for the NOνA detector, and said that they would like to see NOνA proceed on a fast track that maximizes its physics impact. Although the planning is more advanced than other unapproved neutrino proposals, NOνA is not yet as advanced as Fermilab requires for Stage I approval. The PAC listed the steps needed to achieve that approval:

- Finalize the detector design.
- Complete the proposed R&D program.
- Update the proposal to reflect the complete science case.

The PAC strongly endorsed the proposed R&D plan and urged the Laboratory to provide adequate support for timely completion of this program.

4. DESIRED SCHEDULE:

List major milestones (month & year) such as design complete, construction start, construction complete, etc.

December 2004: Final detector technology choices.
June 2005: Fermilab Stage I approval of a complete design.
August 2006: R&D complete.
October 2006: Construction start.
October 2008: Begin Data Taking.

A construction start at the beginning of FY07 would allow the NOνA Near Detector (also off-axis and separate from the MINOS Near Detector) and about 15% of the NOνA Far Detector to be completed by October 2008. A staged construction of the NOνA Far Detector Enclosure is possible, allowing a rapid start to detector construction without a heavy front-loading of the funding profile. Since the NuMI beam will be available throughout this entire period and the NOνA Far Detector is modular, useful data taking would begin during 2008.

December 2011: Construction complete.

5. ROUGH ESTIMATE OF COST RANGES:

Whatever the best information available (eg. $M +/-30~50%, $150~250M, etc.). Total cost range including non-DOE funding (if any other funding sources are assumed and if known, state from where and how much. Also indicate remaining R&D cost to go.

Cost estimates of several NOνA designs have been done following the principles used in costing and tracking the MINOS Detector construction project. For each major system the materials and services procurements have been itemized. Based on the source of the estimate a contingency has been assigned to each element of the estimate. Labor tasks associated with each element of the estimate have been estimated using Fermilab labor rates. Costs for Engineering, Design and engineering oversight (EDIA) have been included. Institutional overhead estimates have been included. A project management task has been included.

The total cost estimate for NOνA designs are in the range of $ 147 M – $ 159 M when fully loaded as described above. The line by line contingency estimates give overall contingency levels in the 40 – 43% range. An assumption of 50% contingency would add $ 11 M to the top of the range. As noted below in the R&D section, there are cost drivers under investigation with opportunities for a total cost savings at the level of about $ 12 M or more. So the cost range could be as wide as $ 135 M – $ 170 M. Again, these are <u>fully loaded</u> costs.

Non-DOE funding sources are likely (e.g. there is a substantial UK interest in the collaboration list) but are not assumed. About $ 1.0 M – 1.5 M of R&D cost remains to go.

6. DESIRED NEAR TERM R&D:

Major activities needed to be completed before start construction.

R&D efforts are now totally focused on liquid scintillator designs for NOνA. Two liquid scintillator designs are being studied, a sampling calorimeter composed of 14% active liquid scintillator and 86% inert PVC and particle board, versus a totally active design composed of 85% active liquid scintillator and only 15% PVC. In both liquid designs the scintillator is constrained in 15 – 18 m long extruded PVC cells with a cell cross section of 10 -20 cm^2. Light from the liquid scintillator is collected in wavelength-shifting fibers routed to Avalanche Photodiodes (APD).

The most important near term R&D goal is to verify the assumed light output level, light collection efficiency, APD photodetection efficiency and electronics designs. Measuring the actual number of photoelectrons detected from the far end of the long extrusions will be the crucial test for this technology. The second near term R&D effort is pursuit of a Cosmic Ray Background Test to determine the charged and neutral cosmic ray backgrounds which would be seen in the detector as it sits on the surface in northern Minnesota. This addresses the need for an active shield composed of detector elements and/or for an earth overburden for the detector. Both these items are large cost drivers. Simulations of the detector response to neutrino interactions and analyses of the detector structural properties will also continue in the near term R&D.

Longer range R&D will investigate Application Specific Integrated Circuits (ASICs) for APD readout with low noise. Investigations of different wavelength shifting fiber diameters and of different pseudocumene concentrations in the liquid scintillator will also be done since these are also large cost drivers with potential for savings in new designs. We estimate a total of $1 M – $1.5 M of R&D materials and services funds will be required during the next two years to advance this proposal at its technically limited pace. Additional contributions of effort from Fermilab and from the other NOνA collaborating institutions are also required.

7. BRIEF DESCRIPTION OF LABORATORY'S ANTICIPATED ROLE:

Expected unique capabilities to be provided by lab. Rough estimate of human resources from lab (#FTE in what type labor).

Fermilab scientists are involved in simulations of the NOνA detector designs and in R&D tests of detector sub-assemblies. The R&D effort is drawing on the laboratory's engineering expertise in finite element analysis of the NOνA mechanical structures and on engineering expertise in the design of NOνA ASICs. Fermilab Lab E will be the location of the Cosmic Ray Background Test described in the R&D section above. One Fermilab scientist is currently co-spokesperson of the NOνA Collaboration, and another is a member of the seven-person NOνA Executive Council.

We anticipate that NOνA prototypes will use the Fermilab testbeam facilities in future years. This could include use of a neutrino testbeam downstream of the Fermilab Debuncher since this machine acts like a muon storage ring neutrino source (of low intensity) during pbar production for Tevatron collider operations.

As in the case of NuMI, it is expected that Fermilab project management, ES&H oversight, financial oversight and procurement would be utilized for a NOνA construction project. Like MINOS, the NOνA design involves a Near Detector in the 300-foot deep NuMI underground enclosure on the Fermilab site. It is anticipated that as in the case of MINOS, this detector would be a major responsibility for Fermilab. Construction of the NOνA Far Detector is expected to involve several factories for production of small modules to be assembled at the far location. Fermilab could be the site for one such factory.

FTEs are difficult to estimate, but currently about 2 FTE scientists and about 1 FTE engineer are involved. The Fermilab human resource effort for NOνA could be anticipated to grow to more like the size of the MINOS (not NuMI) effort at Fermilab which is about 4 FTE scientists, 1 FTE engineer, and 17 FTE technicians during the current installation phase of the MINOS Near Detector.

In addition to the detector, NOνA would be critically dependent on the number of protons the Fermilab accelerator complex delivers to the NuMI target. The sensitivity of NOνA depends on the simple product of neutrino flux times the NOνA Far Detector mass. The NOνA proposal assumes Fermilab can provide 4×10^{20} protons per year, and reaching that goal will require substantial effort from the laboratory. Current Fermilab plans for upgrades to the accelerator chain for MiniBooNE and MINOS will be directly applicable to NOνA. In addition, upgrades to the Main Injector RF to reduce the Main Injector cycle time would immediately benefit NOνA. Such RF upgrades have been studied only conceptually so far. Similarly a future Fermilab Proton Driver would allow NOνA to follow a natural scientific progression to CP violation studies in the neutrino sector. This incremental approach allows for decisions at each step of the program based on scientific outcomes from the previous steps, taking into account new results from other experiments, as well as funding constraints.